KNOWLEDGE-BASED CONTROL SYSTEMS DESIGN FOR FLUID POWER SYSTEMS

Elmar Vier, **Benno Stein** [1]

Department of Measurement and Control (Prof. Dr.-Ing. H. Schwarz), Faculty of Mechanical Engineering, University of Duisburg, D–47048 Duisburg, Germany
Email: vier@uni-duisburg.de

Dept. of Mathematics and Computer Science (Prof. Dr.-Ing. H. Kleine Büning), Knowledge-based Systems, University of Paderborn, D–33095 Paderborn, Germany
Email: stein@uni-paderborn.de

Abstract: Hydraulic control systems are mainly applied to driving problems which require both a high power output and advantageous dynamic properties. A great number of components have to work together in order to perform the complex functionalities requested. Therefore, a huge effort has been spent in developing software solutions to support the engineer with the demanding and time-consuming task of hydraulic control systems design.

There are numerous tools tackling the modelling, simulation, and analysis of hydraulic drives. The evaluation and especially the modification of the investigated system normally is left to the user. This paper elaborates on those aspects of the design procedure which are, up to now, not covered by software systems for hydraulic systems—contributing to 'closing the gap' in the iterative design cycle. In this context, human strategies are worked out, formalized and systematized following a knowledge-based approach.

Keywords: Computer Aided Control Systems Design, Artificial Intelligence, Knowledge-based Systems, Hydraulic Circuits.

1. INTRODUCTION

The design process for hydraulic control systems obtains its complexity from the great variety of qualitative and quantitative requirements to be met. The engineer's design procedure is oriented to the fulfillment of all specified demands on the hydraulic plant which can be roughly divided into the following items:

- Guarantee requested characteristics concerning power output and dynamic behaviour,
- hold given boundary conditions,
- make use of optimization potentials.

In general, the relations within a hydraulic system, that lead to meeting the demands, can not be overlooked and foreseen entirely. Thus, a solution is not found in one single step. Rather will the human expert apply a procedure based on an initial design idea (preliminary or rough design) which then is worked out and developed further step by step. The fundamental design steps are depicted in figure 1.

At first, the *initial design* is subject to analysis. This step comprises the modelling and simulation of the system behaviour based on formulating and solving a set of nonlinear (differential) equations (Schwarz, 1991; Backé, 1992). In the following step the analysis results are evaluated via a comparison with the specified demands. If there are any unfulfilled demands, a modification of the topical design is required entering an iterative cycle. The iteration process carries on until a satisfactory status is achieved providing the *final design* as solution of the design problem.

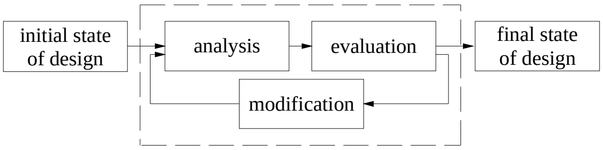

Figure 1: Iterative cycle of control system design.

Every single step within this procedure is demanding and time-consuming. Moreover, it requires a deep understanding of related fields such as hydraulics, electronics, measuring devices, control theory etc.

Here, there is an automation potential that has motivated the development of numerous software tools . A summary of recent software for hydraulic systems is given by Murrenhoff (1996). To support the engineer, these tools address a variety of subtasks by using different approaches to the design problem (cf. Piechnick and Feuser, 1994; Kett and Brangs, 1996; Ionescu and Vlad, 1997).

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Based on the software system $^{\text{art}}$*deco* (Lemmen, 1995; Stein, 1995) the paper in hand follows a knowledge-based approach which has been outlined in (Vier *et al.*, 1996) and substantiated in (Stein and Vier, 1997).

The design task is stated to be "still too complex for simple algorithmic solutions or table look up" (Brown and Chandrasekaran, 1989). Utilizing human strategies introduces an additional aspect with respect to solving the problem. For automation purposes the engineer's design skill is worked out, formalized and systematized in this paper. Here, we focus on the modification step, which owns central significance within the design procedure. Although it represents the key to closing the iteration loop, modifying the hydraulic circuit, usually, is left to the user of software systems.

In this context, section 2 provides basic insights in the modification task. The following sections illustrate different aspects of the modification concept accompanied by a typical example.

2. THE MODIFICATION PROBLEM

Designing hydraulic systems a modification is motivated by the evaluation step proving one or more demands being "not fulfilled". The modification step—as a vital part of the iteration cycle—aims at tailoring a hydraulic system to the customer's demands or improving its behaviour within particular respects. Figure 2 depicts an interpretation of the design process according to Puppe (1988): A given, initial configuration of the hydraulic plant is transformed sequentially to the final configuration with the desired behaviour. Applying a certain modification step makes the difference between two configurations.

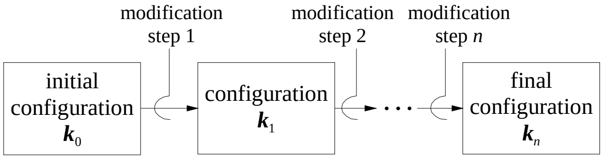

Figure 2: System transformation by modification.

Definition *2.1. Configuration space/configuration*
The configuration space $\mathcal{K}$ represents the fundamental set for all possible configurations of a hydraulic system. A configuration $\boldsymbol{k}$ is given as

$$\boldsymbol{k} = [k_1, k_2, \ldots, k_m] \in \mathcal{K} = \mathcal{K}_1 \times \mathcal{K}_2 \times \cdots \times \mathcal{K}_m \quad (1)$$

and comprises the entire information describing the system, i. e. topological properties, components characteristics and parameters. ❑

The configuration implies a characteristic system behaviour which can be defined as follows

Definition *2.2. behaviour space/system behaviour*
The behaviour space $\mathcal{V}$ represents the fundamental set for all determinable behaviour attributes $\boldsymbol{v}$ with

$$\boldsymbol{v} = [v_1, v_2, \ldots, v_n] \in \mathcal{V} = \mathcal{V}_1 \times \mathcal{V}_2 \times \cdots \times \mathcal{V}_n \ . \quad (2)$$

The mapping $\boldsymbol{v} : \mathcal{K} \mapsto \mathcal{V}$ with $\boldsymbol{v} : \boldsymbol{k} \mapsto \boldsymbol{v}(\boldsymbol{k})$, $\boldsymbol{v} = [v_1(\boldsymbol{k}), \ldots, v_n(\boldsymbol{k})] \in \mathcal{V}$ and $\boldsymbol{k} = [k_1, \ldots, k_m] \in \mathcal{K}$ is called *configuration mapping.* ❑

Designing hydraulic drives those behaviour attributes are of interest which are element of a demand set $\mathcal{A}_i$:

Definition *2.3. Demand profile*
Every subset $\mathcal{A} \subset \mathcal{V}$ is called *demand profile* and comprises all specified demands. According to

$$\mathcal{A} = \mathcal{A}_1 \times \mathcal{A}_2 \times \cdots \times \mathcal{A}_n \subset \mathcal{V} \quad (3)$$

every subset $\mathcal{A}_i \subset \mathcal{V}_i$ $(i = 1, \ldots, n)$ will be called *demand* on a hydraulic system. ❑

Based on definitions 2.1 – 2.3 a function is introduced to judge whether or not demands are fulfilled:

Definition *2.4. Binary evaluation function*
Given a mapping $\boldsymbol{e} : \mathcal{V} \mapsto \mathbb{B}^n := \{0; 1\} \times \cdots \times \{0; 1\}$. If $\boldsymbol{e}(\boldsymbol{v})$ holds

$$\boldsymbol{e}(\boldsymbol{v}) = (e_1(v_1), \ldots, e_n(v_n)) \qquad \text{with} \quad (4)$$

$$e_i(v_i) = \left\{ \begin{array}{ll} 0 & v_i \notin \mathcal{A}_i \\ 1 & v_i \in \mathcal{A}_i \end{array} \right\} \quad (i = 1, \ldots, n) \quad (5)$$

and $\boldsymbol{v} = [v_1, \ldots, v_n] \in \mathcal{V}$, $\boldsymbol{e}(\boldsymbol{v})$ is called *binary evaluation function.* ❑

Figure 3 illustrates the fundamental relations described above. Improving the system behaviour $\boldsymbol{v}$ respecting specified demands $\mathcal{A}$ is based on evaluation results and motivates a modification $\boldsymbol{m}_k$:

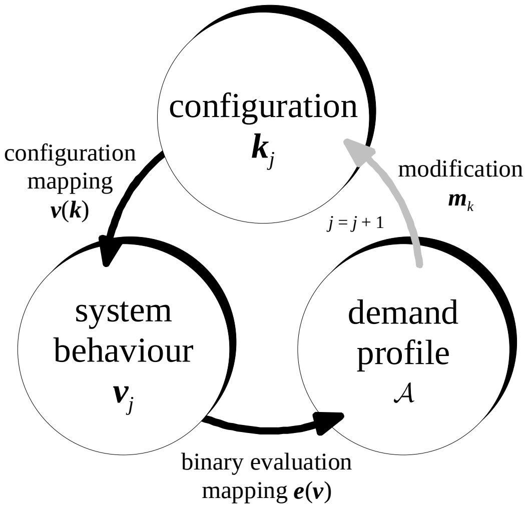

Figure 3: Relations within the design cycle.

Definition *2.5. Modification*
A modification changes the system configuration $\boldsymbol{k}$

respecting at least one configuration attribute k_i ($i \in \{1, \ldots, m\}$). A certain modification is represented by

$$\boldsymbol{m}_k = [i_1, \ldots, i_l] \quad , \; 1 \leq l \leq m \; , \; 1 \leq k \leq r \; , \quad (6)$$

the vector of those indices of the configuration attributes k_i that are changed. ❑

There are two central points raising difficulties within the decision-making process:

- To fulfill the desired demands typically a variety of configurations is suited. Therefore, the effort for reaching this goal must be considerd.
- The strong interdependences within the hydraulic system might lead to modification steps affecting demands previously fulfilled.

Against this background, the following objectives must be considered with priority:

- *Problem solution.* Transform the system to a configuration $\boldsymbol{k}$ that meets all specified demands $\mathcal{A}$.
- *Determination.* Achieve a—possibly steady—behaviour improvement .
- *Convergence.* Finish modification process within a finite number of steps.

In the following, a strategy for an automated control systems design based on the engineer's modification concept is introduced. The main contributions to the decision-making process are:

- The *modification matrix*,
- *local assessment*,
- *modification sequence planning*, and
- *surveillance.*

3. BASIC INFORMATION FOR DECISION-MAKING

For making modification decisions information on the interplay of configuration $\boldsymbol{k}$, behaviour $\boldsymbol{v}$ and fulfillment of demands $\mathcal{A}$ is most important (cf. figure 3): (i) modification measures can be classified regarding their effectiveness. (ii) statements on the solvability of the design problem can be derived. (iii) decoupled subproblems might be addressed separately.

If the vector field $\boldsymbol{v}(\boldsymbol{k})$ is differentiable, the Jacobian

$$\boldsymbol{J}(\boldsymbol{v}, \boldsymbol{k}) = \begin{bmatrix} \dfrac{\partial v_1(\boldsymbol{k})}{\partial k_1} & \dfrac{\partial v_1(\boldsymbol{k})}{\partial k_2} & \cdots & \dfrac{\partial v_1(\boldsymbol{k})}{\partial k_m} \\ \dfrac{\partial v_2(\boldsymbol{k})}{\partial k_1} & \dfrac{\partial v_2(\boldsymbol{k})}{\partial k_2} & \cdots & \dfrac{\partial v_2(\boldsymbol{k})}{\partial k_m} \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{\partial v_n(\boldsymbol{k})}{\partial k_1} & \dfrac{\partial v_n(\boldsymbol{k})}{\partial k_2} & \cdots & \dfrac{\partial v_n(\boldsymbol{k})}{\partial k_m} \end{bmatrix} \quad (7)$$

represents part of these fundamental relations. Using a kind of transformation on matrix $\boldsymbol{J}(\boldsymbol{v}, \boldsymbol{k})$ reveals a direct correlation between the modifications $\boldsymbol{m}_k$ and the behaviour $\boldsymbol{v}(\boldsymbol{k})$: For each modification $\boldsymbol{m}_k$ the information of those columns of $\boldsymbol{J}(\boldsymbol{v}, \boldsymbol{k})$ indicating the related configuration attributes k_i are combined.

Depending on $\boldsymbol{m}_k$, we achieve the representation

$$\boldsymbol{D}_{\mathrm{M}}(\boldsymbol{m}_1, \ldots, \boldsymbol{m}_r; \boldsymbol{k}) = \begin{bmatrix} d_{11}(\boldsymbol{m}_1, \boldsymbol{k}) \cdots d_{1r}(\boldsymbol{m}_r, \boldsymbol{k}) \\ d_{21}(\boldsymbol{m}_1, \boldsymbol{k}) \cdots d_{2r}(\boldsymbol{m}_r, \boldsymbol{k}) \\ \vdots \quad\quad \ddots \quad\quad \vdots \\ d_{n1}(\boldsymbol{m}_1, \boldsymbol{k}) \cdots d_{nr}(\boldsymbol{m}_r, \boldsymbol{k}) \end{bmatrix} \quad (8)$$

which is called *modification matrix.* However, for a number of formal as well as domain specific reasons some of the matrix elements $d_{ik}(\boldsymbol{m}_k, \boldsymbol{k})$ will not be determinable:

- Especially with modifications on the topology of either the hydraulic circuit or the control system, the functional relation may not be known.
- If the function is analytic, at all, it may not be differentiable, in certain cases, or the relating set of definition might be non-metric, i. e. no partial derivative exists.

To evade the problem of incomplete analytic information a heuristic approach is suitable (Harmon and King, 1987). By means of *heuristic approximation* the matrix elements are assigned values $d_{ik} \in [0; 1]$: The stronger the dependence of a behaviour attribute v_i from a modification $\boldsymbol{m}_k$ the higher the value for d_{ik}. Thus, the heuristic modification matrix $\boldsymbol{D}_{\mathrm{M}}$ represents an important modification data-base.

For treating a certain design problem $\boldsymbol{D}_{\mathrm{M}}$ can be reduced as follows: By cancellation of (i) the rows of unconsidered behaviour attributes v_i—for whom there are no demands $\mathcal{A}_i$ specified—and (ii) the columns of non applicable modifications $\boldsymbol{m}_k$ we obtain a submatrix of $\boldsymbol{D}_{\mathrm{M}}$:

$$\boldsymbol{D}_{\mathrm{M}}^{\mathrm{red}} = (d_{ik})_{1 \leq i \leq p, \; 1 \leq k \leq q} \quad (9)$$

is called the *reduced modification matrix.*

Classification of modifications
Classifying modification measures with respect to their efficiency the following definitions are introduced:

***Definition** 3.1. Strong reduced modification matrix*
Given a mapping $\check{R} : \mathrm{Mat}(p, q, \mathbb{R}) \mapsto \mathrm{Mat}(p, q, \mathbb{R})$ with $\boldsymbol{D}_{\mathrm{M}}^{\mathrm{red}} \in \mathrm{Mat}(p, q, \mathbb{R})$. If

$$\check{R}\left(\boldsymbol{D}_{\mathrm{M}}^{\mathrm{red}}\right) := (\check{r}_{ik}(d_{ik}))_{1 \leq i \leq p, \; 1 \leq k \leq q} \quad \text{with} \quad (10)$$

$$\check{d}_{ik} = \check{r}_{ik}(d_{ik}) = \left\lfloor \frac{\mathrm{round}\,(2\, d_{ik})}{2} \right\rfloor \; , \; \check{d}_{ik} \in \{0; 1\} \; , \quad (11)$$

then matrix $\check{\boldsymbol{D}}_{\mathrm{M}} := \check{R}\left(\boldsymbol{D}_{\mathrm{M}}^{\mathrm{red}}\right) =: (\check{d}_{ik})_{1 \leq i \leq p, \; 1 \leq k \leq q}$ is called *strong reduced modification matrix.* ❑

Definition *3.2. Weak reduced modification matrix*
Given a mapping $\widehat{R} : \mathrm{Mat}(p,q,\mathbb{R}) \mapsto \mathrm{Mat}(p,q,\mathbb{R})$ with $\boldsymbol{D}_{\mathrm{M}}^{\mathrm{red}} \in \mathrm{Mat}(p,q,\mathbb{R})$. If

$$\widehat{R}\left(\boldsymbol{D}_{\mathrm{M}}^{\mathrm{red}}\right) := \left(\hat{r}_{ik}(d_{ik})\right)_{1\leq i\leq p,\ 1\leq k\leq q} \quad \text{with} \tag{12}$$

$$\hat{d}_{ik} = \hat{r}_{ik}(d_{ik}) = \left\lceil \frac{\mathrm{round}\,(2\,d_{ik})}{2} \right\rceil \ ,\ \hat{d}_{ik} \in \{0;1\}\ , \tag{13}$$

then matrix $\widehat{\boldsymbol{D}}_{\mathrm{M}} := \widehat{R}\left(\boldsymbol{D}_{\mathrm{M}}^{\mathrm{red}}\right) =: (\hat{d}_{ik})_{1\leq i\leq p,\ 1\leq k\leq q}$ is called *weak reduced modification matrix.* ❑

Theorem *1. Modification classification*
For a certain behaviour attribute v_i the modification $\boldsymbol{m}_k$ will be called
(a) *strong modification*, if

$$\check{d}_{ik} = \check{r}_{ik}(d_{ik}) = 1 \quad , \tag{14}$$

(b) *(ordinary) modification*, if

$$\hat{d}_{ik} = \hat{r}_{ik}(d_{ik}) = 1 \quad \wedge \quad \check{d}_{ik} = \check{r}_{ik}(d_{ik}) = 0\ , \tag{15}$$

(c) *negligible modification*, if

$$\hat{d}_{ik} = \hat{r}_{ik}(d_{ik}) = 0 \quad . \tag{16}$$

Solvability
A necessary condition for addressing the design problem is the existance of at least one modification $\boldsymbol{m}_k$ for each malfunction ($v_i \notin \mathcal{A}_i$), i. e.

$$\sum_{k=1}^{q} |\hat{d}_{ik}| \neq 0 \quad . \tag{17}$$

Decoupability of subproblems
If exists a unique modification $\boldsymbol{m}_k$ for the behaviour attribute v_i *and* $\boldsymbol{m}_k$ has no side effects

$$\sum_{k=1}^{q} |\hat{d}_{ik}| = 1 \quad \wedge \quad \sum_{i=1}^{p} |\hat{d}_{ik}| = 1 \quad , \tag{18}$$

then a modification subproblem is decoupled. Decoupled subproblems are processed with priority, i. e. they are isolated and solved separately, reducing the complexity of the remaining modification problem.

4. LOCAL ASSESSMENT OF ALTERNATIVES

Usually there are alternative modifications $\boldsymbol{m}_k$ to handle a given malfunction. In this case, ranking criteria are required to decide on which modification to apply preferably. This local assessment of modification jobs (cf. figure 4) allows considering optimization potentials within the design process. Currently, the following criteria are employed for evaluation and ranking:

- A modification's *effectiveness* is most important.
- The *repercussion* on the design process describes which design phase—early or late—is affected.
- Another useful criterion is the *effort* required to carry out a modification, if the real plant already exists. Then, modifying parameters, components characteristics or the topological set-up should be distinguished.

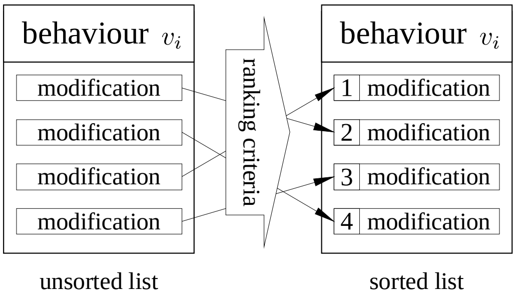

Figure 4: Local assessment of modification jobs.

For ranking purposes, each modification job $\boldsymbol{m}_k$ related to a behaviour attribute v_i is assigned a partial confidence $c_{k,j} \in [0,1]$. The influence of the j criteria —effectiveness, repercussion and effort— is weighted by the confidence factors κ_{ef}[2], κ_{re}, κ_{et}, where

$$\sum_{j} \kappa_j = 1 \qquad \text{with} \quad j = \mathrm{ef}, \mathrm{re}, \mathrm{et} \quad . \tag{19}$$

The absolute confidence C_k of a modification job $\boldsymbol{m}_k$ can be calculated according to

$$C_k = \sum_{j} \kappa_j\ c_{k,j} \qquad \text{with} \quad C_k \in [0;1] \tag{20}$$

to obtain a ranking (cf. figure 4). Applying modifications according to this ranking shall lead to an optimization of the design with respect to the chosen criteria and their weights. If necessary, the number j of criteria can be extended.

5. MODIFICATION SEQUENCE PLANNING

Now, that for every malfunction an appropriate modification has been determined, a decision must be made on which modification step to apply first. It is not advisable, e. g., to optimize a controller while a working element does not provide the desired velocity. Therefore, the modification sequence should be planned in a way to avoid repercussions as far as possible in order to cut down the total number of iterations. For this purpose, the human engineer employs a number of guidelines when designing hydraulic drives. These guidelines are summarized in figure 5.

This type of design skill is utilized to automatically derive a suitable modification sequence: A relation to the sample sequence of hydraulic control systems design is formed respecting two different criteria:

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[2] $c_{k,\mathrm{ef}}$ is identical to the value d_{ik} of $\boldsymbol{D}_{\mathrm{M}}^{\mathrm{red}}$ (cf. section 3).

- In which phase of the sample sequence is the fulfillment of a demand $\mathcal{A}_i$ realized?
- Which phase is affected by a modification $\boldsymbol{m}_k$?

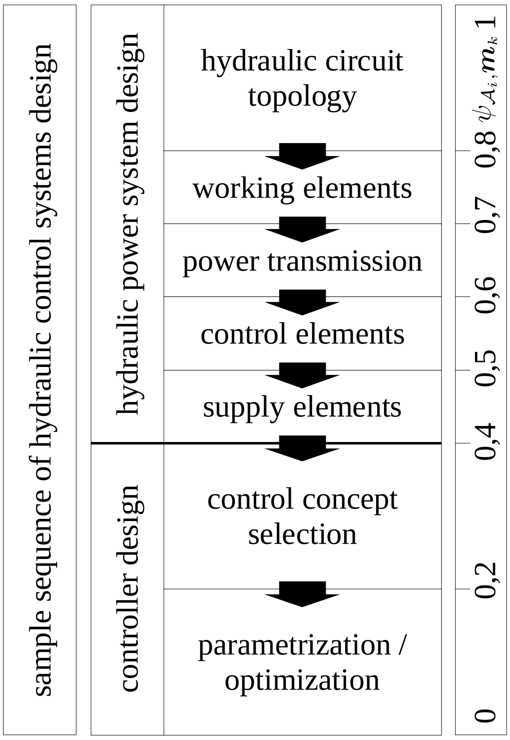

Figure 5: Process of hydraulic control systems design.

Both aspects are represented by influence factors $\psi_{\mathcal{A}_i}$, $\psi_{\boldsymbol{m}_k} \in [0;1]$. Figure 5 shows the differentiation of sequencing steps and the assignment of values to $\psi_{\mathcal{A}_i}$ and $\psi_{\boldsymbol{m}_k}$. Establishing a certain priority for the demand related criterion ($\psi_{\mathcal{A}_i}$), a combined ranking function $\Psi_{ik}(\psi_{\mathcal{A}_i}, \psi_{\boldsymbol{m}_k})$ [3] for modification sequence planning is calculated according to

$$\begin{aligned}\Psi_{ik} &= \alpha_1 \frac{2}{3\pi}\left[\arctan\left(2\,\alpha_3\,(\psi_{\mathcal{A}_i} - 0.5)\right)\right] \\ &+ \alpha_2 \frac{2}{3\pi}\left[\arctan\left(2\,\alpha_3\,(\psi_{\boldsymbol{m}_k} - 0.5)\right)\right] + 0.5\end{aligned} \tag{21}$$

with factors chosen: $\alpha_1 = 0.6$, $\alpha_2 = 0.4$ and $\alpha_3 = \tan\left(\frac{3}{8}\,\pi\right)$. Figure 6 depicts the related performance graph. Applying modification sequence planning as described helps to avoid an undesirable interference among modifications. Hence, it contributes to evading convergence problems for the iterative design process.

6. SURVEILLANCE AND BACKTRACKING

The surveillance step comprises a number of administrative and monitoring tasks. Figure 7 gives an overall view of the different parts contributing to modification decisions. Decision-making starts off from the results of the evaluation step, the modification data-base and user-defined optimization criteria. The modification matrix analyzes the problem on a general level. The surveillance is informed, if non-solvable subproblems are detected. Decoupable subproblems allow taking a shortcut on decision-making via executing the related modifications immediately.

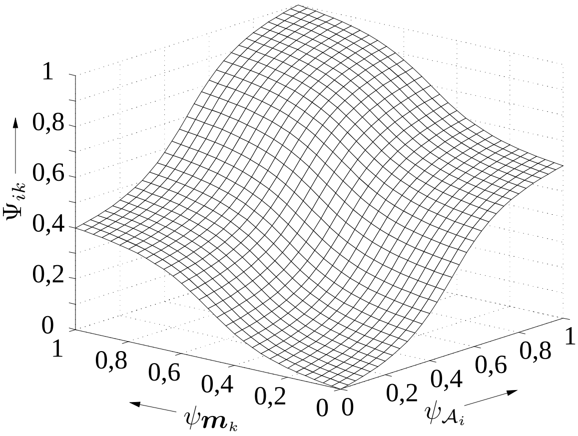

Figure 6: performance graph for $\Psi_{ik}(\psi_{\mathcal{A}_i}, \psi_{\boldsymbol{m}_k})$.

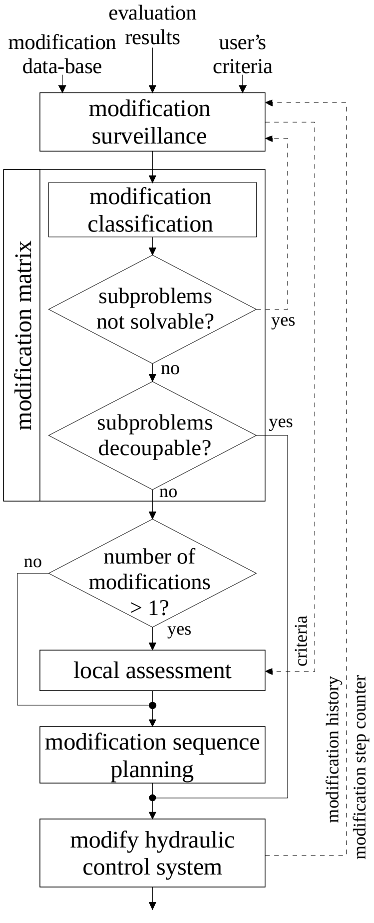

Figure 7: Surveillance and decision-making.

If there are alternative modifications $\boldsymbol{m}_k$ available local assessment is applied utilizing the given ranking criteria. Modification sequence planning provides a chronological order for applying modifications to the plant. Information on the number and type of executed modifications are again reported to the surveillance block. Hence, the progress and success of the modification approach is subject to monitoring raising the possibility to retract actions, if necessary.

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[3] $\psi_{\boldsymbol{m}_k}$ is used as partial confidence $c_{k,\mathrm{re}}$ (section 4).

7. EXAMPLE

To reveal an examplary insight in a relevant modification problem setting, in the following, the local assessment of alternative modifications is demonstrated.

Given a hydraulic control system comprising a valve controlled linear drive as working element. Analysis and evaluation of this oscillatory 2nd order system turned out the behaviour attribute v_i (damping factor $D = 0.08$) to be out of the specified demand set $\mathcal{A}_i = [0.25; 1.25]$. Table 1 comprises a selection of possible modifications.

Modification Measure	$c_{k,\text{ef}}$	$c_{k,\text{re}}$	$c_{k,\text{et}}$	C_k
throttle in sidestream	0.4	0.4	0.5	0.435
throttle in by-pass	0.8	0.4	0.5	0.635
damping network	0.9	0.8	0.1	0.605
velocity feedback	0.6	0.8	0.3	0.525
acceleration feedback	0.8	0.8	0.3	0.625

Table 1. Increasing the system damping D.

The absolute confidence C_k of a modification $\boldsymbol{m}_k$ is computed according to eq. 20 based on the given $c_{k,j}$ and the chosen weights among the criteria, the confidence factors $\kappa_{\text{ef}} = 0.5$, $\kappa_{\text{re}} = 0.15$, $\kappa_{\text{et}} = 0.35$. The local assessment ranks the installation of a throttle valve in a by-pass to the cylinder first option.

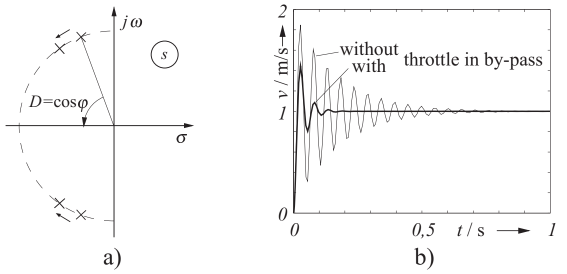

Figure 8: Eigenvalues (a) and step response (b).

The drain flow through the by-pass throttle moves the eigenvalues of the related transfer function to a higher damping (Figure 8 (a)). The step response emphasizes the high effectivenes of this measure (b).

8. CONCLUSION AND FURTHER RESEARCH

The paper in hand introduces approaches to the knowledge-based design of hydraulic control systems. Grounding on a formal problem description a systematics is developed mapping human strategies for processing within a software tool. The modification strategy comprises the utilization of a matrix for classification purposes as well as a solvability and decoupability check.

Alternative modifications are addressed by a local assessment taking into account an extendable number of ranking criteria that can be weighted by the user. To avoid undesired interference of executed modifications, a sequence planning is carried out, in advance. Here, a relation is created between the modification measure, the addressed demand (malfunction) and the related phase within a sample design sequence. Surveillance is required for administrative, and monitoring reasons. It allows to retract actions with undesired effects and motivates the test of alternatives.

Further research work will deal with the implementation of modification strategies within a software environment. Basic concepts for this have been described in Vier and Stein (1998). In this context, the modification knowledge-basis will be extended and applied to a wider range of design examples.

At the same time analysis methods are developed to qualitatively assess the fulfillment of demands. This shall lead to a partially automated influencing of weighting criteria within decision-making.

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